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**NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY
NAVAL AIR STATION, PENSACOLA, FL 32508-5700**

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**AIRCRAFT WINDSCREENS ENHANCE
VISUAL SEARCH DISRUPTION
PRODUCED BY LASER GLARE**

J.A. D'Andrea, R.N. Shull, and J.C. Knepton, Jr.

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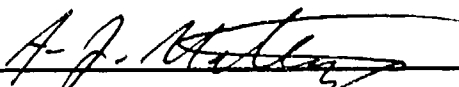
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Volunteer subjects were recruited, evaluated, and employed in accordance with the procedures specified in Department of Defense Directive 3216.2 and Secretary of the Navy Instruction 3900.39 series. These instructions are based upon voluntary informed consent and meet or exceed the provisions of prevailing national and international guidelines.

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ABSTRACT

Naval aircrews may be exposed to laser radiation that is used for a variety of purposes. Consequently, there is a high probability of both deliberate and accidental exposure of naval personnel to laser radiation. One deliberate use of laser radiation may be as a mission deterrent to disrupt aircrew visual performance. The purpose of this study was to determine how low-intensity laser glare interacts with an aircraft windscreen and if flat or wraparound aircraft windscreens differentially enhance glare and disrupt visual search performance. In addition, we evaluated the effectiveness of laser glare in high ambient light. Visual search time to locate target disk viewed through either a flat or curved windscreen under laser glare conditions was significantly longer compared to a no glare control. The glare pattern and disruption of visual search under low ambient light, simulating dawn or dusk, was more extensive when viewed through a wraparound F/A-18 windscreen than a flat A/4 windscreen. Detection of the targets also depended on their location relative to the center of the laser glare pattern. Visual search performance returned to baseline levels under daytime ambient lighting conditions. The results of this experiment illustrate that aircraft windscreens can significantly enhance laser-produced glare as measured by a visual search performed under low levels of ambient lighting. Eye protection is needed to prevent mission disruption, even at laser intensities that are not harmful to the eye.

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INTRODUCTION

Naval aircrews will likely be placed in a combat environment that is saturated with electromagnetic energy emitted from a variety of sources. Laser radiation, serving such tactical applications as countermeasures, rangefinding, and guidance will be included in this environment. Further, the use of laser radiation as a mission deterrent is highly likely and may disrupt aircrew visual performance at intensities much lower than that needed to produce eye damage.

During and after laser exposure, the events which disrupt vision can be classified as retinal damage, flashblindness, or veiling glare (1,2). Historically, a primary concern has been retinal or corneal damage caused by laser irradiation of different wavelengths. At sufficient energy levels, permanent visual impairment will result from lesions caused by thermal or other damage mechanisms on tissues of the eye (2,3). More recently, functional visual impairments that may occur well below the damage threshold have caused some concern (4). Disruption by laser glare of visually guided tasks may be significant and may seriously degrade aircrew performance. Many studies have examined laser-induced retinal lesions, however, the effect of glare and temporary flashblindness produced at low laser intensities have not been sufficiently investigated. Such an investigation should reveal the types of visually guided performance most affected by laser glare. Understanding the variety and severity of laser-glare-induced decrements in visually guided performance will allow for the systematic investigation of countermeasures for reducing deleterious effects.

Visual search is an important aspect of modern aviation. This part of visual performance incorporates locating and identifying targets both inside and outside of the aircraft. An operator's ability to locate targets in a complex background has received much attention in recent years (5), and a variety of factors, such as number of searched elements, total display information, number of targets, and target defining dimensions, are known to influence visual search. Also, recent research has begun the investigation of temporal uncertainty in a continuous search experimental paradigm (6-8). For naval operations, a pilot's ability to read individual aircraft instruments from the display or locate targets in the air and on the ground are examples of visual search tasks.

Our previous research has demonstrated that low-level laser glare ($0.09\text{--}0.20 \mu\text{W}/\text{cm}^2$), presented under low ambient lighting simulating dawn or dusk, is very effective in disrupting target acquisition during visual search of a complex array through an A/4 windscreen (9). The windscreen scatters laser light and enhances glare, while low ambient lighting results in increased retinal sensitivity and consequently a greater susceptibility to laser-produced glare. Most important is the fact that a subject's speed and accuracy of target acquisition were not disrupted by laser glare at low intensities unless the windscreen was in the visual path.

Several other windscreen factors such as shape, surface imperfections, method of fabrication and construction material may be important and influence glare produced by low-level laser irradiation and subsequent visual search performance. In this study, we conducted two experiments. The purpose of the first experiment was to compare, under low ambient light, the effects of low-intensity laser glare and shape of the windscreen on target acquisition performance. We tested target acquisition performance during visual search with and without either a flat (A/4) or curved (F/A-18) aircraft windscreen. In the second experiment we evaluated visual search performance through an A/4 windscreen during laser glare under high ambient light.

MATERIALS AND METHODS

SUBJECTS

Eight volunteer aviation candidates served as subjects in experiment 1. Their average age was 23.5 years with a range of 22-29 years, and all had at least 20/20 near snellen binocular visual acuity as measured with the Armed Forces Vision Tester (Model FSN 7610-721-9390, Braun-Brumfeld, Inc., Ann Arbor, MI).

Six volunteer aviation candidates served as subjects in experiment 2. Their average age was 23.5 years with a range of 22-25 years, and all had at least 20/20 near snellen binocular visual acuity as measured with the Armed Forces Vision Tester.

EQUIPMENT

Laser and Laser Safety

A coherent light beam generated by an argon ion laser (Innova 70-2, Coherent Laser Products Division, Palo Alto, CA) was conducted by fiber optics to the center of a visual display set up in an adjacent room (Fig. 1). Laser beam intensity was reduced using beamsplitters and neutral density filters and focused on the polished end of an optical grade fiber-optic cable by a fiber-light coupler (Newport No. 714/965-5406). The fiber-optic cable (2.2-mm od) consisted of a single-strand core of acrylic polymer (1.0-mm diam) with a fluorine-polymer sheath. The distal end of the fiber-optic cable projected a 30° cone of laser light toward the cockpit and subject.

An electronic shutter (Newport No. 845) was placed in the beam path before the fiber-light coupler to control delivery of laser light to the subject. The final intensity of the laser beam (before the light coupler) was controlled using different neutral density filters to produce a power density of 0.20 $\mu\text{W}/\text{cm}^2$ at eye level in the cockpit simulator with or without the windscreen in the visual path.

The laser was always operated at full output power and subsequently reduced to a desired intensity for display to the subject. An overexposure could only occur by failure of the mechanical barriers (beamsplitters and filters), which was highly unlikely as these were exposed to light intensities far below design limits. In addition, four separate laser-defeat switches were strategically located, including a defeat switch in the cockpit. A standard operating procedure developed for this laser adhered to the ANSI Z136.1 1986 safety standard (10). The risk of accidental overexposure to laser light near the far end of the fiber-optic cable was prevented by mechanical barriers that blocked subject access to the projection screen. The hazard zone at the projection screen was 10 cm from the display end of the fiber-optic cable. All experiments were supervised by a naval medical officer.

Laser Power Levels and Radiometry

Laser output power was monitored constantly with a power meter (Coherent 2000) and a strip-chart recorder (Soltec model VP-6223S). Laser intensity at the subject's eye level in the cockpit with the windscreen was measured before each test session with a radiometer (United Detector Technology model 61) and a laser power meter (Coherent model 212). Mean drift in the power output of the laser was less than 3%. Power-level values at the subject never exceeded 10% of the ANSI (10) maximum permissible exposure (MPE) standard. The maximum time that the laser beam was projected on the subject during a visual display was 20 s. Therefore, the total time that a subject could be exposed during an experimental session was 1600 s (30 trials x 20 s).

Cockpit Simulator

Either an A/4 or F/A-18 aircraft windscreen assembly was fitted to the cockpit-familiarization trainer (Fig. 2). The windscreens could be easily removed by simply unfastening four mechanical retainers and lifting them from a black foam rubber cradle fitted to top of the cockpit. Measured light transmission of the visual search task through the windscreens varied between 60 and 67% depending on windscreen measurement location. Subjects were monitored visually using closed-circuit television. Voice contact was maintained with the subject at all times with a voice-actuated intercom system located near the cockpit.

Visual Stimulus Array

The visual-search task was a modification of that described by Cole and Jenkins (11). The task contained 80 separate displays, each composed of 119 background disks and 1 target disk (Fig. 3). The displays were constructed on a microcomputer (Zenith Z-248) and plotted on white paper using an x-y plotter (Graphtec MP-2000). Each display was then photographed on high-contrast negative film, which was then mounted in a 35-mm cardboard slide holder.

A field extending 7.6° horizontally and 7.6° vertically was projected onto a plastic rear-projection screen (Daplex No. DA-1N, 122 x 122 cm) 1.70 m from the subject's eye for experiment 1 and 1.35 m for experiment 2. A slide projector (Kodak Ektagraphic No. AF-2) fitted with a zoom lens (Navitar NZ-70125) was used to project the slides. An electromechanical shutter was used to control projection of each slide (Ilex Optical Co. No. 22-8437).

The background of the field was a random arrangement of disks containing a target disk, which was the smallest disk in the array. All background disks viewed at 1.35 m were 17.8 min arc, and the target disk was 14.0 min arc. At a viewing distance of 1.70 m, the background and target disks were 14.2 and 11.1 min of arc, respectively. The disks occupied approximately 14.2% of the total stimulus area.

Two incandescent lamps (Westinghouse Soft White 75 W) were mounted behind plastic diffusing plates and behind the rear-projection screen. Contrast between the disks and the field was achieved by controlling the intensity of the lamps with a variable transformer to backlight the rear-projection screen and projected-disk images. The room housing the cockpit was illuminated by an overhead house lamp (Westinghouse Soft White 75 W), which was dimmed by a variable transformer.

The visual-search task display was evaluated using a photometer (Photo Research Pritchard No. PR-1980A) and a fast spectral scanning system (Photo Research No. PR-713AM Spot Spectrascan). In experiment 1, the overhead lamp provided a mean luminance of 0.27 and 0.28 cd/m² measured through the A/4 and F/A-18 windscreens and 0.42 cd/m² without the windscreen. In experiment 2, the mean luminance was 274 cd/m². These were measured at the projection screen surface with a 100% reflectance standard (Photo Research RS-1). Measured without the windscreens, mean luminance (\pm SEM) of five disks projected on the viewing screen with the backlights was 8.0 ± 0.27 cd/m², and mean luminance (\pm SEM) of the field (including backlights) adjacent to each disk was 5.9 ± 0.28 cd/m². The contrast between disks and the field was 0.33, 0.25, and 0.39 with the A/4 and F/A-18, and without the windscreen, respectively. A "rest" field between each display had a mean luminance of 5.98 cd/m² without the windscreen. The color temperature of a disk near the center of the display was 2146 K with a peak spectral radiance at 1062 nm. The 1960 C.I.E. color coordinates of this disk were $u = 0.2936$ and $v = 0.3592$. The background adjacent to this disk was 1926 K with peak spectral radiance at 1066 nm and C.I.E. coordinates of $u = 0.3112$ and $v = 0.3597$.

Each display was divided into four equal quadrants by a small cross projected on the center of the screen. Each display contained a single target disk located in one of the four quadrants. In experiment 1, which compared the A/4 and F/A-18 windscreens, the targets were located at eccentricities from the center of the display at 0.58, 1.16, 1.74, 2.11, and 2.49°. In experiment 2, which evaluated the A/4 windscreen under high ambient lighting, the targets were located at eccentricities from the center of the display at 0.7, 1.4, 2.2, 2.6, and 3.1°. Targets were always placed randomly within a quadrant (counterbalanced across eccentricities) at least two target diameters away from quadrant boundaries to avoid uncertainty in reporting the target quadrant.

Experimental Control and Data Acquisition

Experimental contingencies and data collection/storage were under microcomputer control (Zenith Z-248). An analog and digital input/output board (Metrabyte Corporation model DASCON-1) and solid-state controllers (BRS/LVE, Inc.) were used to monitor response switches, advance slide projectors, control laser and slide-projector shutters, and provide audio feedback to subjects. A compiled algorithm written in BASIC source language was used for computer instructions to integrate the various experimental functions.

Visual Assessment

Subjects were tested before and after laser exposure to ensure that visual capabilities were not degraded. Vision assessment tests were conducted after one of the training sessions and again following the first laser session. Subjects were tested on central acuity (Armed Forces Vision Tester), contrast sensitivity with and without central glare (Vistech, Multivision Contrast Tester), and color discrimination (Farnsworth-Munsell 100-Hue Test, Macbeth, Division of Kollmorgen Corp., Baltimore, MD).

PROCEDURES

Subjects were seated in an airplane cockpit simulator and asked to search each display (120 disks) for a target (1 smaller disk). They reported which of four quadrants contained the target disk by depressing one of four corresponding switches mounted on their kneeboard. An experimental session contained 80 screen displays (trials) interrupted by a 1-min rest after the first 40 displays. Each display was presented for 20-s or until the subject made a choice on the kneeboard. The subject advanced to the next trial by pressing a handheld switch. Different tones presented by a small speaker (10-cm diam) located next to the cockpit signaled right or wrong choice of quadrant for the target disk. Another tone indicated the end of a session.

Before testing, each subject received an oral briefing on the task requirements and a set of written instructions on details of the task, emphasizing both speed and accuracy in locating and reporting targets. Subjects were given training sessions to stabilize performance prior to laser exposure. In experiment 1, each subject was given seven training sessions. In experiment 2, they received four training sessions. In experiment 1, subjects viewed the displays through each windscreen or no windscreen in a counterbalanced order over the seven training sessions. Both experiments used a forced-choice repeated-measures experimental design where each subject served as his own control. Performance on the last training session was used as baseline.

During glare test sessions, laser light from the argon ion laser was projected toward the subject (approximately a 30° cone) from the center of the cross-and-disk array on the projection screen using the fiber-optic light guide. After training, subjects in experiment 1 were given three daily test sessions in low ambient light: A/4 windscreen, FA/18 windscreen, and no windscreen. They viewed the display through one laser light intensity adjusted to be equal with or without the windscreens in the visual path. Subjects in experiment 2 were given two laser glare test sessions in high ambient light: A/4 windscreen or no windscreen. Visual search time (VST) and post search time (PST), were recorded for each of the 80 trials given per day. The VST was the elapsed time from start of a display until the subject pressed a quadrant button on the knee pad. The PST was defined as the elapsed time from pressing a button on the keypad until the subject initiated the next trial with the handheld switch.

RESULTS

EXPERIMENT 1 - WINDSCREEN COMPARISONS IN LOW AMBIENT LIGHT

Training data and laser data for experiment 1 were analyzed separately, and only correct target-location responses were considered for analysis of VST and PST. A completely within-subjects repeated-measures analysis of variance design was used to evaluate training and laser glare data. All pairwise post-hoc comparisons among means were carried out using the Tukey HSD test at an 0.05 probability level.

The subjects learned the visual search task very rapidly over the 7-day training period. Both VST and PST improved over days (VST- $F(6, 238) = 29.8, p < .01$; PST- $F(6, 238) = 27.9, p < .01$) and were essentially stable after the fourth training session ($p < .05$). Subjects made very few mistakes in choosing the correct target quadrants.

As shown in Fig. 4, VST for targets at each eccentricity and was significantly increased by laser glare, which depended on eccentricity of the target ($F(12, 133) = 12.3, p < .01$). At the first and second eccentricities (0.58° and 1.16°), VST with laser glare for both windscreens and no windscreen were significantly longer than VST for the last training session. At 1.16° , VST with laser glare and no windscreen was significantly less than VST with A/4 and FA/18 windscreens. At the third and fourth eccentricities (1.74° and 2.11°) VSTs for the last training session, no windscreen, and A/4 windscreen were significantly less than for the FA/18 windscreen. Also, training and no windscreen VSTs at both eccentricities (1.74° and 2.11°), were significantly less than for the A/4 windscreen. Finally, at the fifth eccentricity (2.49°) VST for the last training session and no windscreen glare was significantly less than for both windscreen conditions.

Post search time for targets at each eccentricity of the last training session differed significantly from laser glare with and without the windscreens ($F(3, 133) = 3.24, p < .05$). During training and laser glare, PST was significantly longer at the middle eccentricities (1.74° and 2.11°) than eccentricities near the periphery of the display ($F(4, 133) = 12.0, p < .01$). Post search time simply increased after a laser glare trial and did not produce a change in this pattern.

EXPERIMENT 2 - LASER GLARE IN HIGH AMBIENT LIGHT

Visual search time and through the A/4 windscreen with and without laser glare in high ambient light is shown in Fig. 5. Visual search time increased significantly across eccentricity ($F(4, 10) = 11.14, p < .001$). There was also a significant increase in VST attributable to the three conditions ($F(2, 10) = 7.84, p < .01$). The interaction of exposure condition and eccentricity was not significant. A comparison of means showed that the differences between training and windscreen VSTs at each of the five eccentricities was not significant. We found no significant differences in PST for the three experimental conditions (training, windscreen, no windscreen) or across eccentricity.

Finally, subjects were tested before and after laser exposure in both experiments to ensure that normal vision was not altered. Subjects showed no differences before and after laser exposure on our measures of central acuity, spatial contrast sensitivity with and without glare, or color discrimination.

CONCLUSIONS

The effect of laser light on visual performance at an intensity well below that causing eye damage has not received a great deal of attention. Our results here replicate our earlier study (9) showing that laser light intensities far lower than the ocular-damage level may still effectively disrupt aircrew visual search performance. This effect was observed in experiment 1 under low ambient light levels and occurred primarily for target searches through the A4 and FA/18 windscreens. Without the windscreens, visual search

performance approximated that of the training levels except at the near eccentricity. In this case, laser glare without the windscreen was sufficient to obscure targets at 0.58° of eccentricity.

We observed significant differences in the extent of the glare produced by the different windscreens. We believe that laser light scatter from the windscreens produced a glare enhancement that effectively masked target location more extensively for the FA/18 than the A/4 windscreen. Target masking, however, lasted only for the duration of laser exposure. This is noted because the percentage of targets correctly identified did not differ significantly from training performance. Laser exposure ended after 20 s, which allowed the subject to search for the target unimpeded by the glare source. In most instances when the 20-s limit ended the exposure, subjects subsequently located the target very quickly. As evidenced by their quick PSTs of less than 1 s, subjects did not hesitate to initiate each trial. Because PSTs at the eccentricities closest to the laser source (0.58° and 1.16°) did not significantly change between training and laser exposure sessions, laser intensities used here were probably not aversive to the subjects--otherwise PSTs would have increased during laser exposure conditions, especially at target eccentricities near the center of the beam path.

As we suspected, laser glare at an irradiance of $0.20 \mu\text{W}/\text{cm}^2$ was not very effective in increasing VST under high ambient light. With the windscreen VHTs at each of the eccentricities did not differ significantly from those established during training. An increase in laser irradiance of at least an order of magnitude is probably needed to produce any target masking under high ambient light. We did not attempt to establish this threshold due to the constraints of the long viewing times used here and the MPE established by the ANSI exposure standard. Lasers may produce effective glare during daylight, but the increase in irradiance necessary would reduce the effective range unless the laser output power could be increased significantly.

In summary, we conclude that glare produced by low level laser light interacts with windscreen characteristics to degrade visual search performance. The intensity of glare used in this study can easily be produced by relatively low-power lasers ($< 10 \text{ W}$) many kilometers downrange. Laser eye protection is needed during night operations, not only to prevent eye injury, but also to preserve aircrew mission capability at laser glare intensities below damaging levels. Further research is ongoing in our laboratory to evaluate laser eye protection under low ambient light and to test windscreens at other laser wavelengths.

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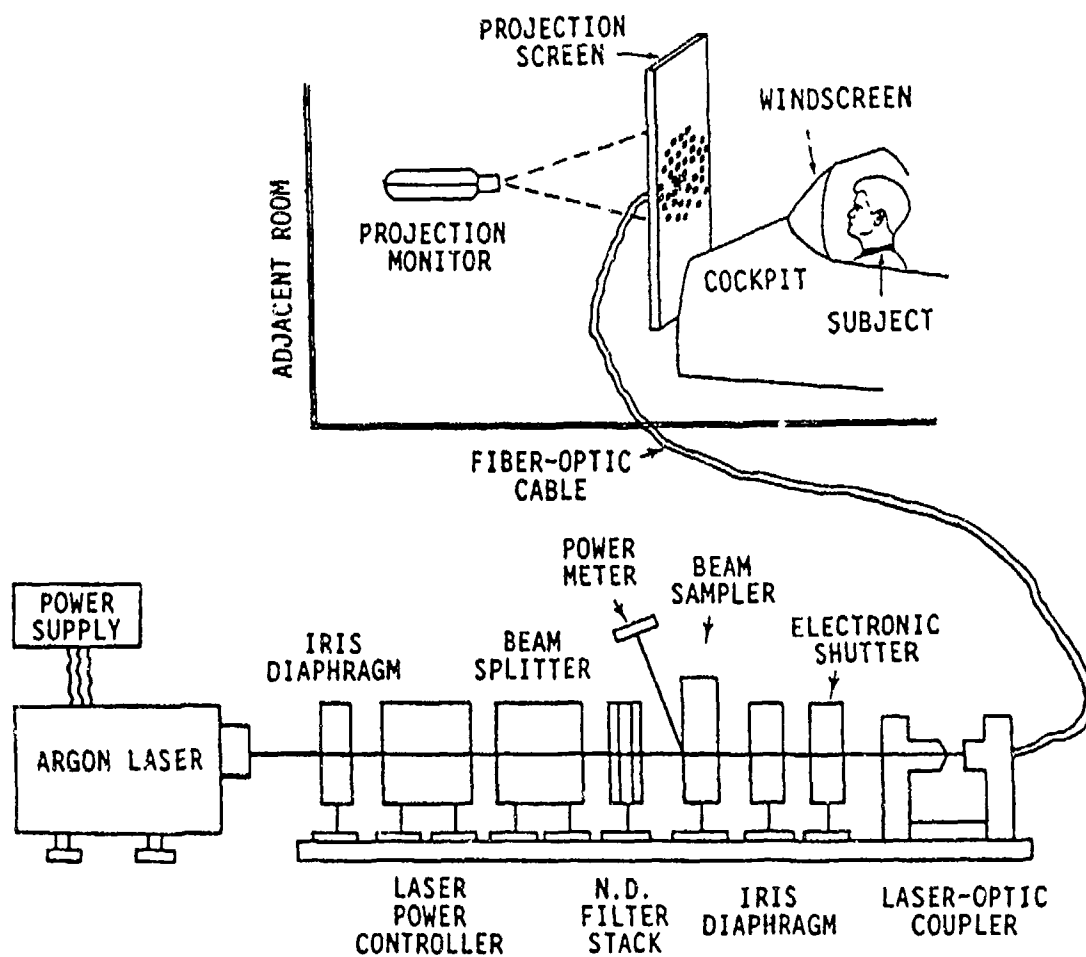
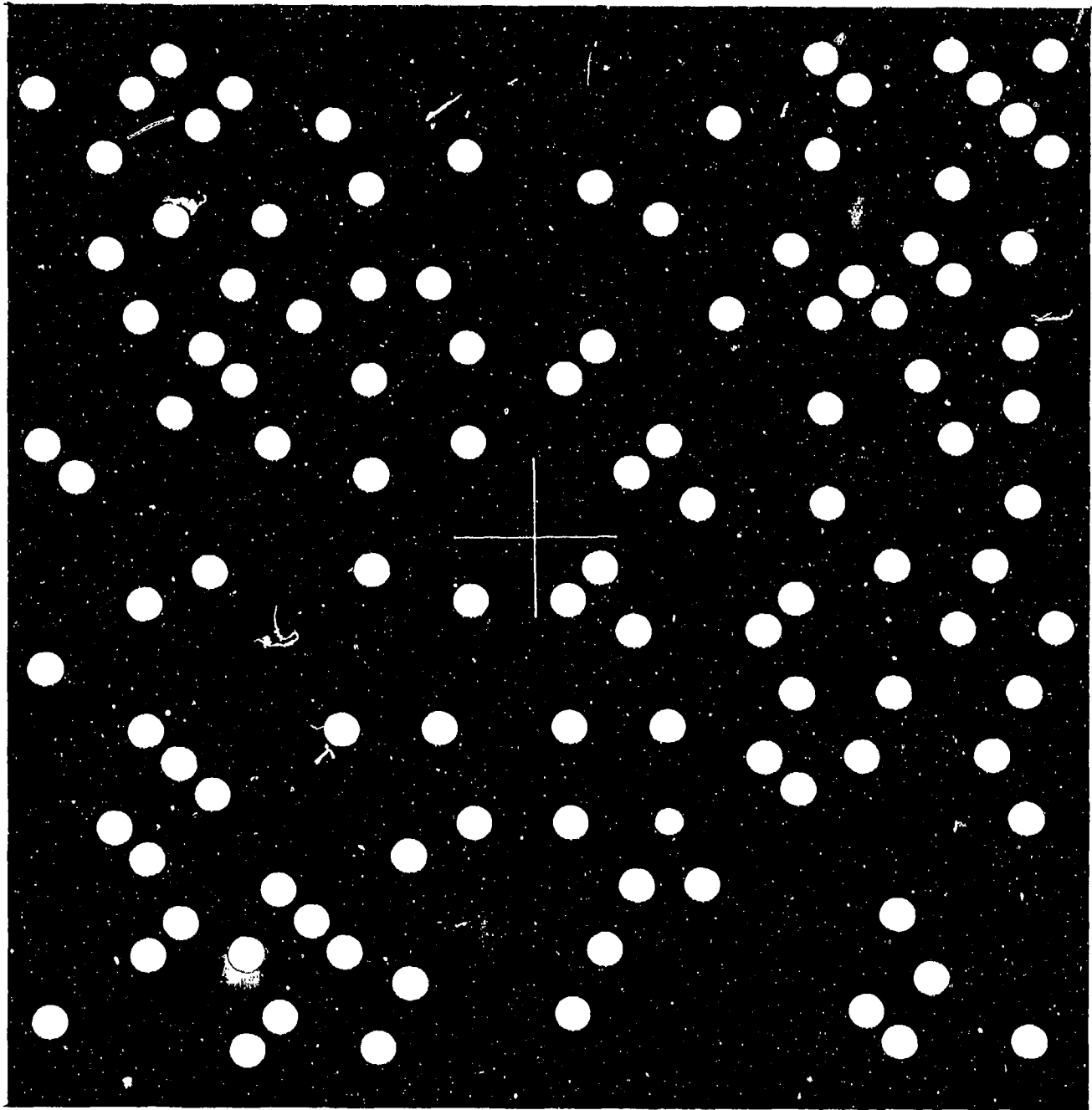


Figure 1. Schematic representation of laser and cockpit layout.



Figure 2. Subject seated in cockpit simulator behind A/4 windscreen performing the visual search task.6



3. Typical visual search display.

LOW AMBIENT LIGHT

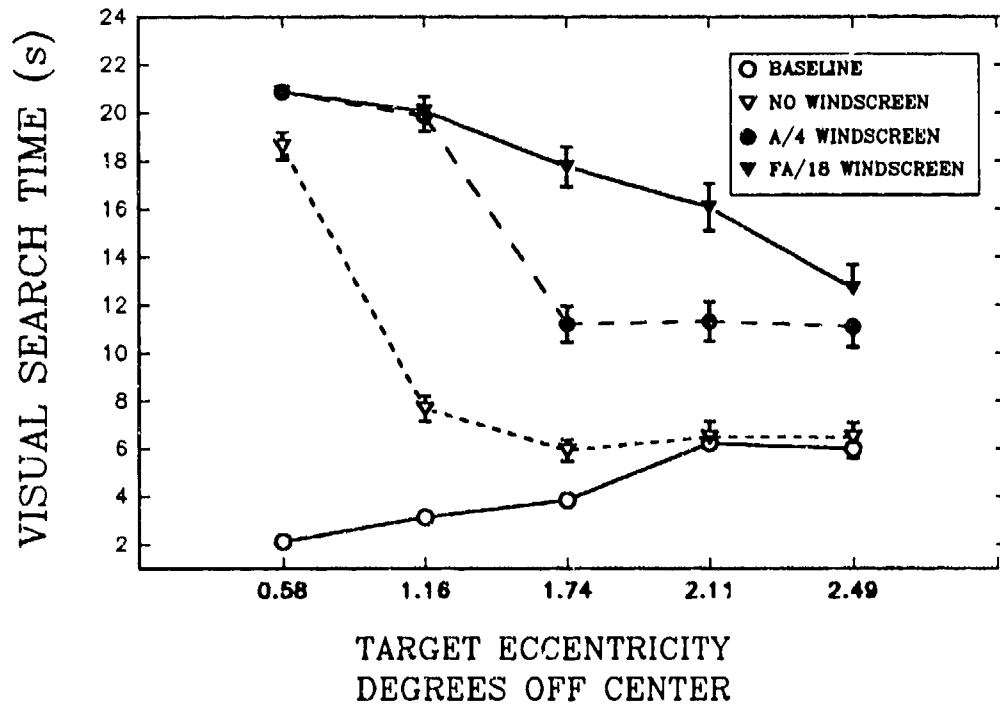


Figure 4. Mean (\pm SEM) visual search time (VST) in seconds for experiment 1.

HIGH AMBIENT LIGHT

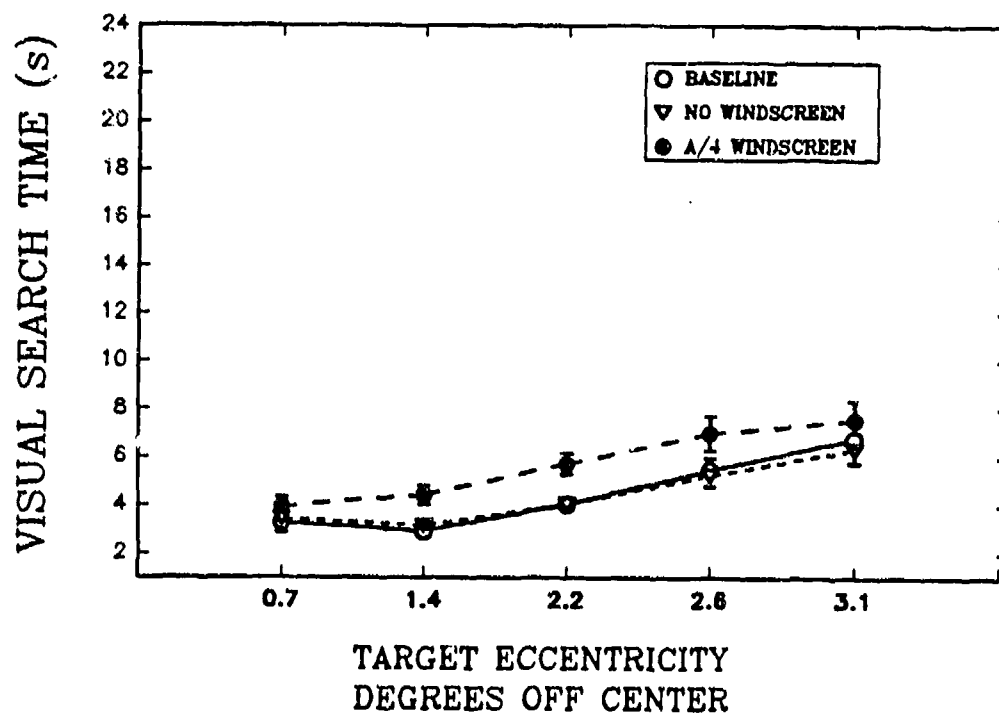


Figure 5. Mean (\pm SEM) visual search time (VST) in seconds for experiment 2.

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